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The Planck-Balance – primary mass metrology for industrial applications

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Abstract. The Planck-Balance is a new weighing instrument, that utilizes the Kibble principle for mass measurements. In contrast to existing Kibble experiments the balance is aimed at applications in industrial or research use. The proposed new definition of the kilogram with a fixed value of the Planck constant will allow primary mass measurements with electrical measurements using the Kibble principle. Two instruments, PB2 and PB1 will be developed in a joint research project of the Physikalisch-Technische Bundesanstalt (PTB) and the Technische Universität Ilmenau, funded by the German Federal Ministry of Education and Research. The aimed measurement range is from 1 mg to 100 g and 1 mg to 1 kg with a relative measurement uncertainty according to E2 and E1 accuracy classes, respectively, as specified in OIML R 111-1. For the determination of the measurement uncertainty a virtual Planck-Balance will be set up, that uses Monte Carlo simulation to determine measurement uncertainties during the measurement process.

1. Introduction
In 2019 a proposed new definition of the kilogram, based on a fixed Planck constant, will most probably replace the currently effective definition. This results in mass measurements that must be traceable to the value of the Planck constant. The Kibble principle, used recently for the determination of the Planck constant, provides a path for mass determination via electric measurements, without the need for calibrated weights and is thus a primary method for mass determination [1]. Current Kibble balances are complicated, large and expensive experiments that are only feasible for a selected number of national metrology institutes and are suitable only for a very limited range of mass values.
The Planck-Balance (PB), currently under development in a joint project of the Physikalisch-Technische Bundesanstalt and the Technische Universität Ilmenau, is a weighing instrument intended for industrial applications, using the Kibble principle. It will offer user-friendly access to a primary method for mass determination with a wide measurement range beginning from 1 mg designed for the requirements of industrial applications.

2. Concept of the Planck-Balance
The general concept focuses on industrial applications and results in different design goals compared to the established Kibble experiments. In the project two balances, with different aimed specifications,

will be developed. The balances will be called PB2 and PB1. The names for the balances come from the aimed measurement uncertainties corresponding to accuracy levels E2 and E1 for weights, as specified in OIML R-111-1 [2]. Table 1 shows the aimed specifications for both balances. The PB2 will be the starting point for the PB development and perform as the base line for improvements towards the PB1. The relative measurement uncertainty u_{rel} results from the definition of the maximum permissible error MPE and the minimum of allowed relative uncertainty $u_m(\text{max})/m(\text{max})$, which is at the top of the weight range.

Table 1. Aimed specifications for the two balances to be developed in the Planck-Balance project.

	PB2	**PB1**
Mass range	1 mg … 100 g	1 mg … 1 kg
MPE /m(max) [a]	16×10^{-7} (E2)	5×10^{-7} (E1)
$u_{rel} = u_m(\text{max})/m(\text{max})$ ($k = 1$)	2.7×10^{-7} (E2)	8.4×10^{-8} (E1)
Measurement environment	air	high vacuum
Duration of the measurement cycle	10 – 120 s	10 – 120 s

[a] MPE is the maximum permissible error of a weight

To accelerate the development, the design will rely on standard components readily available to order from manufacturers. Using standard components as far as possible leverages the result of decades of research and development and allows to concentrate efforts on the parts where the performance of currently available standard components is not sufficient for the design goals.

For an efficient development process of two balances the design of both balances will be highly modularized. The PB1 will be developed from the PB2 by replacing the performance constraining parts, but keeping everything else the same. This also opens an upgrade path that allows future customers to upgrade components from the PB2 to PB1 components in order to increase the performance of their weighing instrument.

Since user-friendliness is an important design aspect for the use in industrial applications, the balance should be as compact and lightweight as possible. It is aimed to design a table top device for the mechanical part of the balance, accompanied by a rack for electrical measurement devices.

3. Components of the Planck-Balance

This section will present the key components of the PB2 and provide details on the magnet system for the PB2 and the motion deviations of the linear guide. Additionally, the determination of the measurement uncertainty with a virtual Planck-Balance VPB will be shown. The main components of the PB are shown in figure 1.

The traceability of the results is achieved via the electrical measurements and their quantum standards. The voltage measurements are traced to the Josephson effect and the resistor to the quantum hall resistance. Furthermore, the velocity measurement of the dynamic measurement mode and the measurement of the local gravity requires traceability to time and length standards, resulting in traceable measurements without the use of any mass artefacts.

3.1. Magnet system of the PB2

There are no commercial magnet systems available that fulfil the high performance requirements of the PB. The underlying Kibble principle requires a magnet system with a high 'force factor' Bl, the product of the coil length and the magnetic field strength in the gap where the coil moves. With a high Bl the induced voltages for practical coil velocities can be measured with low measurement uncertainties. The PB2 magnet system is based on magnet systems currently used in commercially

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available EMFC load cells. The configuration of these magnets corresponds with the BIPM-type as described in [1]. While keeping the yoke and the permanent magnets, the coil of the magnet system will be upgraded to a coil with more windings and a carrier-less design. In order to reduce the self-heating due to power loss in the upper mass range, three identical magnet systems will be stacked onto each other and compensate the mass of the weight together.

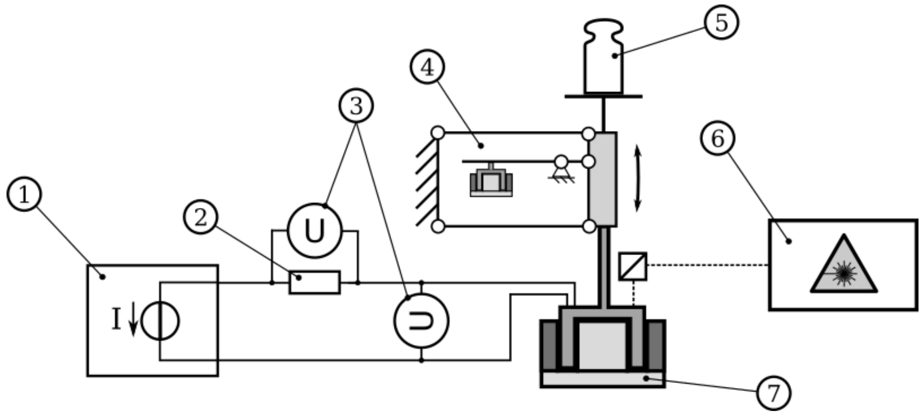

Figure 1. Main components of the Planck-Balance with controllable current source (1), standard resistor (2), digital voltmeter (3), electromagnetic force compensating (EMFC) load cell (4), weight to be measured (5), laser interferometer (6), and magnet-coil system (7). Not shown is a frequency standard for synchronizing all measurements.

3.2. Motion deviation of the EMFC load cell

The EMFC load cell performs as a linear guide in the PB. The measurement procedure of the Kibble principle is only valid if the properties of the magnet system do not change when switching between the dynamic and the static measurement mode. Motion deviations of the linear guide can induce measurement errors or increase the measurement uncertainty during the dynamic measurement. The angular motion deviation of the EMFC load cell used in the PB2 has been measured with a three-beam interferometer and was found to be less than ±100 nrad, whereas a tilt of 45 µrad corresponds to a relative error of 1×10^{-9} [3]. This means, that the linear guide properties of the EMFC load cell are very well suited for the requirements in the PB.

3.3. Virtual Planck-Balance

Measurement uncertainty determination with Monte Carlo simulation has the advantage that complex or non-linear model functions can be handled without increased mathematical complexity [4]. This will be accomplished by the virtual Planck-Balance (VPB). Like the PB it consists of several subsystems. These subsystems, like the laser interferometer or the voltmeter are modelled individually as *virtual devices* and will be able to exchange data with each other. Each virtual device contains a model function, considering all relevant input variables including error sources, like the ambient conditions, that influence the device. The virtual device then determines the current measurement uncertainty, considering systematic and random errors occurring during the measurement.

A digital twin of the measurement device can be received by extending the virtual device with individualized data of the device. This digital twin is equipped with a unified and well documented communication interface, that enables the communication and data exchange between other digital twins. Since calibration data is an important part of the individual data representing a measurement device, the PTB has developed a digital calibration certificate, that will be used to store and exchange the calibration data of digital twins [5].

As a first step towards VPB the digital twin of a weight has been set up at the PTB, modelling the influences of the weight itself on the measurement result. The digital twin considers the effects of air buoyancy, cleaning status of the surface, and the height of the centre of mass of the weight as well as time dependent changes of the measurement uncertainty. As shown in figure 2, the digital twin of a weight can be used to distribute the calibration information and individualized model function of a weight in a user-friendly and accessible way.

Figure 2. Weight with dedicated digital twin on a USB drive

4. Conclusion

The Planck-Balance, a new weighing instrument, is currently under development and will be able to do primary weight measurements via electrical quantities by means of the Kibble principle. The weighing instrument will finally cover a measurement range from 1 mg to 1 kg and the aimed relative measurement uncertainty ($k = 1$) will be 8.4×10^{-8} for 1 kg. Since the instrument is aimed at industrial applications the development focusses on the use of standard components and a compact size of the final instrument. The uncertainty determination will be done during the measurements with a virtual Planck-Balance based on Monte Carlo simulations, considering error sources that influence the result while the measurement process is running.

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